

## ORIGINAL PAPER

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## Role of transpiration suppression by evaporation of intercepted water in improving irrigation efficiency

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**Abstract** Sprinkler irrigation efficiency declines when applied water intercepted by the crop foliage, or gross interception ( $I_{\text{gross}}$ ), as well as airborne droplets and ponded water at the soil surface evaporate before use by the crop. However, evaporation of applied water can also supply some of the atmospheric demands usually met by plant transpiration. Any suppression of crop transpiration from the irrigated area as compared to a non-irrigated area can be subtracted from  $I_{\text{gross}}$  irrigation application losses for a reduced, or net, interception ( $I_{\text{net}}$ ) loss. This study was conducted to determine the extent in which transpiration suppression due to microclimatic modification resulting from evaporation of plant-intercepted water and/or of applied water can reduce total sprinkler irrigation application losses of impact sprinkler and low energy precision application (LEPA) irrigation systems. Fully irrigated corn (*Zea Mays* L.) was grown on 0.75 m wide east-west rows in 1990 at Bushland, TX in two contiguous 5-ha fields, each containing a weighing lysimeter and micrometeorological instrumentation. Transpiration ( $Tr$ ) was measured using heat balance sap flow gauges. During and following an impact sprinkler irrigation, within-canopy vapor pressure deficit and canopy temperature declined sharply due to canopy-intercepted water and microclimatic modification from evaporation. For an average day time impact irrigation application of 21 mm, estimated average  $I_{\text{gross}}$  loss was 10.7%, but the resulting suppression of measured  $Tr$  by 50% or more during the irrigation reduced  $I_{\text{gross}}$  loss by 3.9%. On days of high solar radiation, continued transpiration suppression following the irrigation reduced  $I_{\text{gross}}$

loss an additional 1.2%. Further 4–6% reductions in  $I_{\text{gross}}$  losses were predicted when aerodynamic and canopy resistances were considered. Irrigation water applied only at the soil surface by LEPA irrigation had little effect on the microclimate within the canopy and consequently on  $Tr$  or  $ET$ , or irrigation application efficiency.

### Introduction

Irrigation increases and stabilizes crop yields in the semi-arid Great Plains. Irrigation efficiency can be defined as the ratio of total water stored in the root zone for plant use to the total amount of water applied (Hansen 1960). Most sprinkler irrigation water losses are due to evaporation of water intercepted by and held on the foliage, or gross interception ( $I_{\text{gross}}$ , in mm/h) loss, of airborne droplets either inside or outside the irrigation application area, and of water ponded at the soil surface. In a study on corn using precision weighing lysimeters (9 m<sup>2</sup> surface area), the lysimeters measured net irrigation application catches which averaged 81% for impact sprinklers and 96% for the low energy precision applicators (LEPA) for an average application depth of 20 mm (Schneider and Howell 1990).

In irrigation management, the proportion of the total applied water that a plant canopy can store for evaporation is important, and is a function of leaf size. During an irrigation, the plant canopy will accumulate water as it evaporates until its storage capacity is reached, when drip-off occurs. After an irrigation, the stored water will continue to evaporate until the canopy is dry. Measured storage capacity values for corn include 0.4–0.7 mm (Stoltenberg and Wilson 1950), 2.7 mm (Steiner et al. 1983a), and 1 mm for a leaf area index  $\approx 4$  (Norman and Campbell 1983). Norman and Campbell (1983) suggested that evaporation of plant-intercepted water from canopies with small leaves, such as wheat, might be as much as 10 mm for a single event under high evaporation conditions.

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These irrigation efficiency losses, however, can also be expected to supply some of the atmospheric evaporative demands usually met by plant transpiration. Transpiration can be reduced both during and after an irrigation in response to the lowered vapor pressure deficit (increased ambient air humidity and reduced air temperature) created when evaporation occurs. In the altered microclimate, the plant benefits through a reduction in heat stress and maintenance of soil water reserves normally being depleted by transpiration. According to McNaughton (1981), any "savings", or decline, in crop transpiration from the wetted area as compared to a non-irrigated area can be subtracted from gross interception losses for a reduced, or net, interception ( $I_{net}$ , in mm/h) loss. He predicted an upper limit of net interception loss to be about 10% of the applied water for any but the highest evaporative demand conditions.

The importance of  $I_{net}$  loss is controlled by the magnitude of the differences between dry and wet leaf evapotranspiration (ET, in mm/h) during and after an irrigation. Wet leaf ET greatly exceeding dry leaf ET suggests that atmospheric demands were not being largely met by transpiration ( $Tr$ , in mm/h). Monteith (1965) and Rutter (1975) pointed out that the ratio between wet leaf and dry leaf ET is a function of crop canopy resistance ( $r_c$ , in s/m) and the aerodynamic resistance to vapor transport ( $r_{av}$ , in s/m). When  $r_c$  and  $r_{av}$  are similar in size, the rate of wet leaf ET will not much exceed the rate of dry leaf ET. McMillan and Burgoyne (1960), Frost (1963), and Seginer (1967) found similar ET rates for wetted and dry crops (with non-limiting soil water and therefore low  $r_c$ ). However, when  $r_c$  is an order of magnitude greater than  $r_{av}$ , wet leaf ET will be 3 to 5 times that from a dry canopy, a condition which also exists for well-watered crops during irrigations at night, early in the morning, and late in the evening. Waggoner et al. (1969) reported short-term evaporation rates of corn wetted with 0.3–0.5 mm of water that were over 2.5 times that of a dry canopy, both being measured by lysimeters. Differences greater than 500% were noted when the dry canopy was slightly water stressed (stomata partially closed). They showed the effect lasted only a short time (about 10 min) during typical summertime conditions in Connecticut until the canopy dried and the ET rates became the same.

The microclimatic modification due to irrigation has been reported by Robinson (1970), who measured consistent reductions in air temperature and increases in vapor pressure of 1.16 kPa at a 0.3-m height over an alfalfa field that had been sprinkler irrigated, and an increase of 0.49 kPa in a field that had been flood irrigated. Steiner et al. (1983b) reported significant declines of almost 1.8 °C for both seasonal means of maximum and minimum leaf temperatures under sprinkler irrigation.

The objective of this research was to determine the extent in which transpiration suppression resulting from microclimatic modification due to evaporation of plant-intercepted and/or applied irrigation water can reduce sprinkler irrigation application losses from day time impact sprinkler and low energy precision application (LEPA) irrigation events for fully irrigated corn.

## Materials and methods

Corn (*Zea Mays* L., hybrid Pioneer 3124<sup>1</sup>) was planted on 0.75-m wide east-west rows in 1990 at Bushland, TX in two contiguous 5-ha fields. A weighing lysimeter (Marek et al. 1988), with a 9-m<sup>2</sup> surface area and 2.3-m depth containing a monolithic profile of Pullman clay loam (fine, mixed, thermic Torriertic Paleustoll), is centered in each field (Fig. 1). Mass changes due to water loss were measured with a lever scale with a mechanical advantage of 100:1 and counterbalanced so that about 10% of the lysimeter mass was measured by a 22.7-kg load cell providing an ET accuracy of 0.05 mm of water. Plant densities on the two lysimeters were 5.4 and 6.1 plants/m<sup>2</sup>.

Each lysimeter was instrumented with one mast to measure net radiation [model Q 5.5, Radiation Energy Balance Systems, Inc. (REBS), Renton, WA], and oblique (15° field of view) and nadir (60° field of view) canopy temperature [model 4003 infrared thermometer (IRT), Everest Interscience, Inc., Fullerton, CA]. The oblique and nadir IRT measurements were averaged for canopy temperature values used in calculations. The instruments were located at 1 m above the crop surface.

Wind speed (cup anemometer model 014 A, Met One, Inc., Grants Pass, OR) profile, and air temperature and vapor pressure profiles were measured separately on two masts in close proximity to each lysimeter. Periods with wind speeds less than 0.5 m/s were excluded from analysis. Air temperature and vapor pressure were determined from aspirated wet- and dry-bulb psychrometers similar to that described by Lourence and Pruitt (1969). Normally, the wind speed and temperature instruments were located at 1.0, 1.3, 1.8, and 2.8 m above the crop surface. Just prior to an irrigation, the wet- and dry-bulb psychrometer, radiation, and anemometer masts were lowered to allow clearance of the lateral move irrigation system. During this period, wind speed was estimated based on regression of wind speed at 1.8 m above the crop on 2-m or 10-m wind speed (over grass) at a weather station adjacent to the lysimeter fields, and net radiation was estimated as  $0.77^*R_s$ , where  $R_s$  is solar radiation (W/m<sup>2</sup>) measured at the weather station. The radiation and anemometer masts were returned to normal elevations above the crop surface as soon as possible (5–10 min after system crossover). To measure within-canopy profiles of air temperature and vapor pressure deficit (VPD, in kPa) during and following an irrigation, the wet- and dry-bulb psychrometer mast remained within the canopy, usually until the following day. When within the canopy, the psychrometers were at 0.36, 0.66, 1.16, and 2.16 m above the ground surface. Following anthesis [about day of year (DOY) 210], the top psychrometer was approximately 0.1–0.2 m below the crop canopy surface.

Soil heat flux at each lysimeter was measured using four soil heat flux plates (REBS model HFT-1) (two in furrows and two in rows) at the 0.05-m depth. The soil heat flux was corrected for the heat storage in the 0–0.05-m depth as determined from soil temperature in that layer and the heat capacities of the minerals, organic matter, and water content soil constituents.

Transpiration of three to four plants on each lysimeter was estimated from sap flow measured with heat balance sap flow gauges (Dynamax, Inc. Model SGB-19) based on designs by Baker and Van Bavel (1987). Mean mass sap flux was converted to a transpiration flux (kg h<sup>-1</sup> m<sup>-2</sup>) on an areal basis by multiplying the mean plant (p) density (p/m<sup>2</sup>) by the mean mass sap flux (kg h<sup>-1</sup> p<sup>-1</sup>). This approach assumed that individual plants selected for sap flow measurement are representative of the entire population (Ham et al. 1990). Transpiration was occasionally overestimated for brief periods in the morning, possibly related to the changes in water capacitance of the plant.

Soil moisture was kept above 75% of field capacity with a 450-m long lateral move irrigation system equipped with overhead impact sprinklers located about 4.3 m above the ground and LEPA devices (Lyle and Bordovsky 1981, 1983) 0.3 m above the ground.

<sup>1</sup> The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-Agricultural Research Service

The Senninger 6° impact sprinklers (model 4006) had 6.75 mm (17/64 in) diameter nozzles and operated at about 210 kPa pressure. They were placed at 6.1-m intervals along the mainline, and had an average 30-m wetted diameter and a peak application rate of 16 mm/h. The LEPA devices (Rainbird) were metered through Senninger 360° Super Spray devices with 3.18 mm (1/8 in) nozzles that operated at about 225 kPa pressure. The LEPA method had a peak application of 125 mm/h, deposited water into alternating furrows 1.5 m apart, and typically did not wet the canopy. The approximate application rate for the impact sprinklers was  $6.0 \text{ L min}^{-1} \text{ m}^{-1}$  (0.48 gpm/ft; flow rate per unit lateral length) and for LEPA was  $6.4 \text{ L min}^{-1} \text{ m}^{-1}$  (0.52 gpm/ft). This permitted comparisons between paired irrigation events (e.g., sprinkler vs. LEPA, sprinkler vs. none) for wetted and dry canopy transpiration values. Irrigation method was alternated between the two lysimeters. The irrigations occurred near solar noon and the cumulative ET data presented do not represent total daily values.

The micrometeorological and lysimeter data were recorded at each lysimeter with separate dataloggers (model CR-7X, Campbell Scientific, Inc., Logan, UT). The lysimeter load cell data were measured at 1-Hz sampling frequency, with 5-min means and standard deviations recorded. The micrometeorological sensors were measured at 0.17-Hz frequency and recorded as 15-min means. The 5-min lysimeter data and the 15-min micrometeorological data were composited into 30-min mean values. Immediately after an irrigation event, the 5-min lysimeter data were composited into 15-min means for a more detailed analysis of ET.

The irrigation application (Ap, in mm/h) was determined as the net gain in mass of the lysimeter during the irrigation. Since ET could not be measured separately during an irrigation event, gross interception loss, the water intercepted by and evaporated from crop foliage, was approximated as the maximum evaporation rate possible if all the energy supplied to the canopy by net radiation, sensible heat flux, and soil heat flux was used in evaporating intercepted water, or

$$I_{gross} = (R_n + H + G) / \lambda, \quad (1)$$

where  $R_n$  is net radiation,  $H$  is sensible heat flux, and  $G$  is soil heat flux, all in  $\text{W/m}^2$ , with all values positive toward the crop, and  $\lambda$  is the latent heat of vaporization ( $\text{J/kg}$ ) used to convert energy flux into mass loss. Net radiation and  $G$  were measured, with  $H$  estimated as

$$H = (T_a - T_c) \rho C_p / r_{ah}, \quad (2)$$

where  $T_a$  is air temperature ( $^{\circ}\text{C}$ ) measured at 2.16 m above the soil surface,  $T_c$  is canopy temperature ( $^{\circ}\text{C}$ ),  $\rho$  is atmospheric density ( $\text{kg/m}^3$ ), and  $C_p$  is specific heat of moist air ( $\text{J kg}^{-1} \text{ } ^{\circ}\text{C}^{-1}$ ). Aerodynamic resistance to heat transfer,  $r_{ah}$  ( $\text{s/m}$ ), is given as (Hatfield et al. 1984)

$$r_{ah} = r_{am} (1 + 5 Ri), \quad (3)$$

where  $r_{am}$  ( $\text{s/m}$ ) is the aerodynamic resistance to momentum transfer (Thom 1975) calculated by

$$r_{am} = \ln[(Z-d)/Z_{om}]^2 / (k^2 U_z), \quad (4)$$

The Richardson number ( $Ri$ ) is used as a stability correction (Monteith 1963, 1973) and is estimated by

$$Ri = |g(T_a - T_c)(Z-d)| / (T_a U_z^2), \quad (5)$$

where  $Z$  is reference height (m),  $k$  is von Karman's constant (0.41),  $U_z$  is wind speed (m/s) at reference height  $Z$ ,  $T_a$  is the average temperature taken as  $[(T_a + T_c)/2]$ ,  $d$  is displacement height (m), determined from (Monteith 1973) as

$$d = 0.63 h, \quad (6)$$

where  $h$  is crop height (m), and  $Z_{om}$  is roughness length for momentum (m), given as (Monteith 1973)

$$Z_{om} = 0.13 h. \quad (7)$$

Estimated net interception loss ( $I_{net(ET)}$ , in mm/h) is defined as the gross interception loss minus the difference in transpiration of a wetted crop canopy ( $Tr_w$ , in mm/h) and a dry crop canopy ( $Tr_d$ , in mm/h) or

$$I_{net(ET)} = I_{gross} - (Tr_w - Tr_d). \quad (8)$$

Predicted net interception loss ( $I_{net(p)}$ , in mm/h) during an irrigation (McNaughton 1981) was calculated by

$$I_{net(p)} = (52 - T_c) \times 10^{-3} r_c U^* ET, \quad (9)$$

where  $U^*$  is friction velocity (m/s). The McNaughton equation is a simplified advection model representing evaporation suppression in the wetted area due to increased humidity, lowered temperature, and a reduced sensible heat flux compared with the unwetted area. Evapotranspiration was measured and  $r_c$  calculated immediately prior to the irrigation event. Canopy resistance was calculated as (Szczec et al. 1973)

$$r_c = \{ \rho C_p (e_c^* - e_a) / (\gamma \cdot \lambda ET) \} / r_{ah}, \quad (10)$$

where  $e_c^*$  is saturated vapor pressure (kPa) at canopy temperature ( $T_c$ ),  $e_a$  is ambient vapor pressure (kPa),  $\gamma$  is the psychrometric constant ( $\text{kPa/}^{\circ}\text{C}$ ), and  $\lambda ET$  is latent heat flux ( $\text{W/m}^2$ ).

Friction velocity was estimated from the log-law wind speed profile by

$$U^* = 0.4 U_z / \ln[(Z-d)/Z_{om}]. \quad (11)$$

## Results and discussion

Transpiration, measured ET, and vapor pressure deficit responses to LEPA (L) irrigation ( $Tr_L$ ,  $ET_L$ , and  $VPD_L$ ) and no (D) irrigation ( $Tr_D$ ,  $ET_D$ , and  $VPD_D$ ) are shown in Figs. 2 and 3 for DOY 218 (08/06/90). Prior to the irrigation, wind speed was  $<2 \text{ m/s}$  and air temperature  $22^{\circ}\text{C}$ . Neither  $VPD_L$ ,  $Tr_L$ , or  $ET_L$  were substantially altered due to microclimatic modification resulting from evaporation of surface water. While Norman and Campbell (1983) modeled comparable  $Tr$  and soil water evaporation rates in a wet soil/dry canopy case, they noted that the importance of evaporation from a wet soil surface is a function of soil and crop characteristics and environmental conditions.

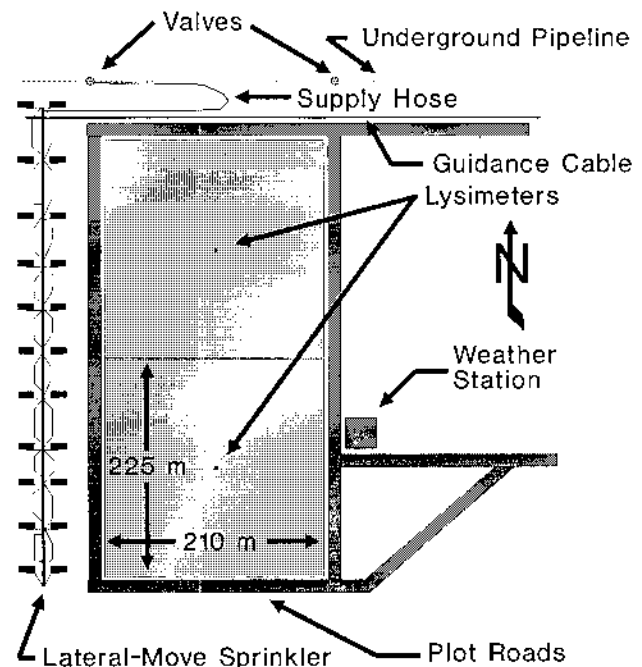
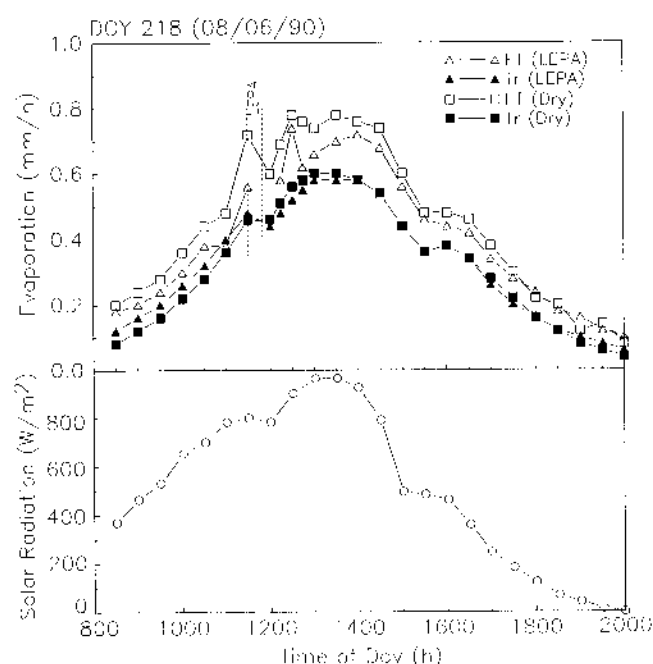
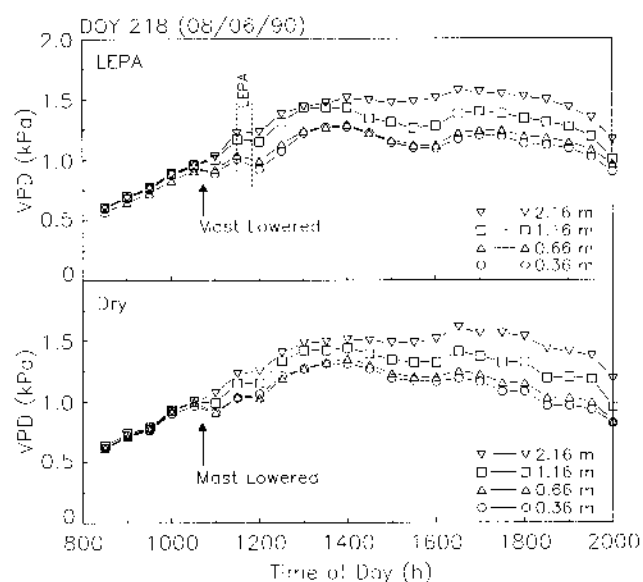


Fig. 1 Overview of lysimeter field, associated weather station, and lateral move sprinkler irrigation system

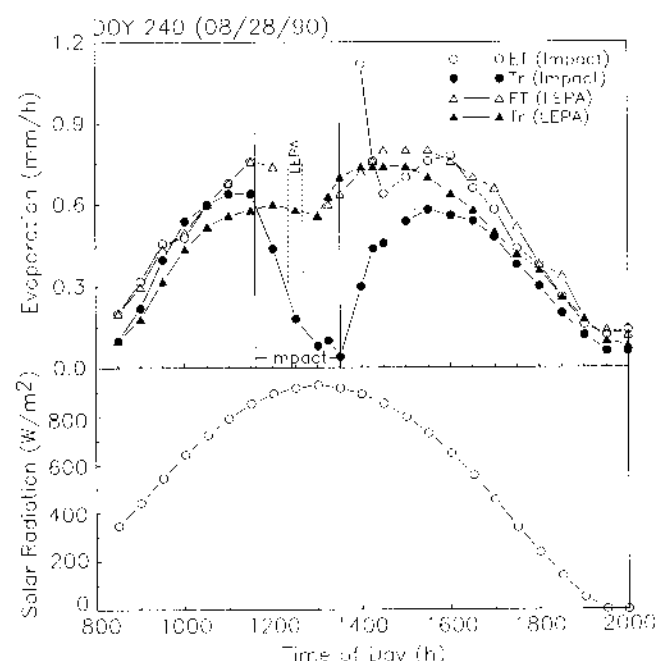


**Fig. 2** Measured evapotranspiration (ET) and transpiration (Tr) for concurrent LEPA irrigation and no irrigation events, and associated solar radiation. Vertical lines represent the beginning and end of the irrigation

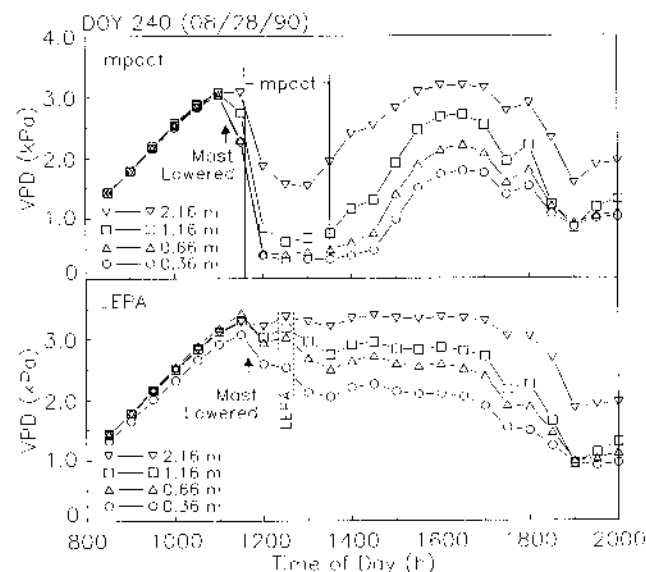


**Fig. 3** Changes in within-canopy vapor pressure deficit (VPD) during and after LEPA irrigation and no irrigation events. Vertical lines represent the beginning and end of the irrigation

Although  $ET_D$  and  $ET_L$  paralleled each other immediately following the irrigation for 0.25 h (Fig. 2, 1215–1230 h), from 1245–1330 h  $ET_L$  declined 0.14 mm compared with  $ET_D$  while  $Tr_L$  and  $Tr_D$  remained similar. This response suggests that humidification of the environment was sufficient to briefly suppress soil water evaporation, but not



**Fig. 4** Measured evapotranspiration (ET) and transpiration (Tr) for concurrent impact sprinkler and LEPA irrigation events, and associated solar radiation. Vertical lines represent the beginning and end of the irrigations



**Fig. 5** Changes in within-canopy vapor pressure deficit (VPD) during and after impact sprinkler and LEPA irrigation events. Vertical lines represent the beginning and end of the irrigations

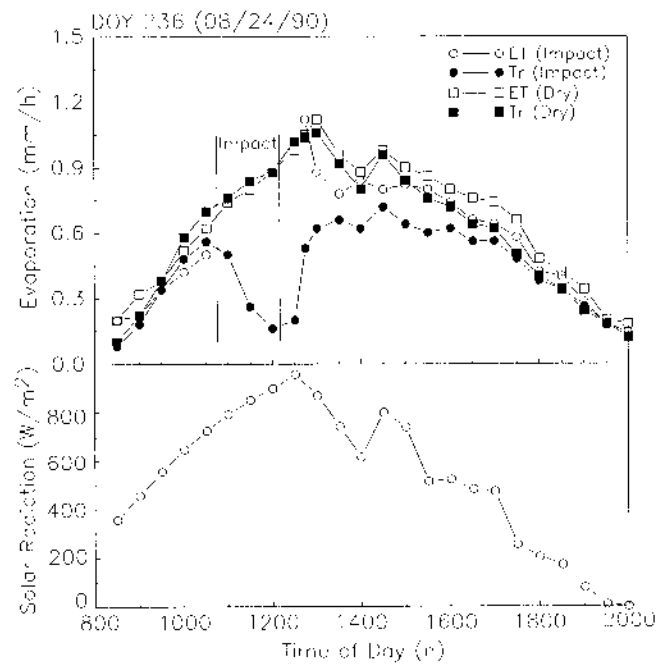
transpiration. A slight drop in  $VPD_L$  occurred at the 0.36 m and 0.66 m measurement levels (Fig. 3). Similar small, brief declines in  $ET_L$  but not  $Tr_L$  also occurred on DOY 198 (07/17/90) on both lysimeters (data not shown). However, on DOY 240 (08/28/90), a clear day with fairly high vapor pressure deficits, the LEPA irrigation caused a notice-

able response in both  $ET_L$  and  $Tr_I$ , with a 0.14 mm/h decline between pre- and post-irrigation  $ET_L$  and possibly a 0.04 mm/h drop in  $Tr_L$  between 1200–1300 h (Fig. 4). The VPD, measured by the two lower psychrometers during the impact sprinkler irrigation also fell 0.5 kPa during this period (Fig. 5).

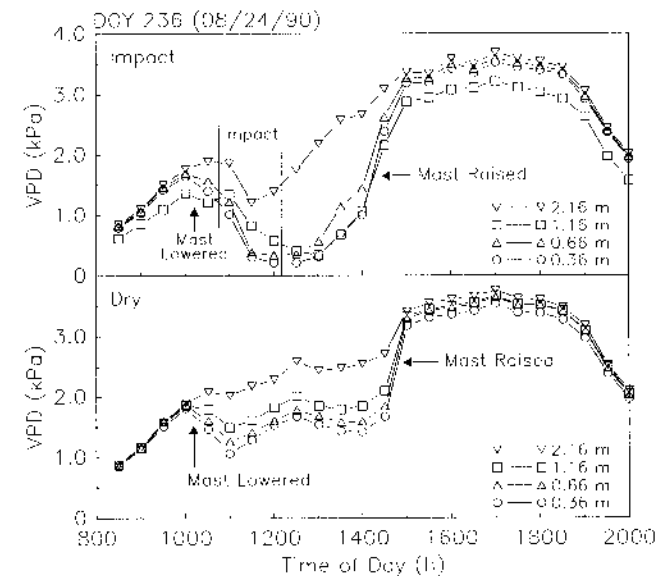
On DOY 236 (08/24/90), drops in measured  $ET$ ,  $Tr$ , and VPD of impact sprinkler (I) irrigation ( $ET_I$ ,  $Tr_I$ , and  $VPD_I$ ) compared with no irrigation suggest a strong response to microclimatic modification (Figs. 6 and 7). Prior to the irrigation, wind speed was 3–4 m/s and air temperature was 30°C. Near the end of the irrigation (1200 h),  $VPD_I$  at the lower two measurement levels had declined 1.4 kPa lower than  $VPD_D$  and  $Tr_I$  0.7 mm/h lower than  $Tr_D$ . Canopy temperature of the impact sprinkler irrigated crop ( $T_{c(I)}$ ) dropped 5.3°C (Table 1). Impact sprinkler transpiration and canopy temperature recovered to near dry levels rapidly (1 h), unlike  $VPD_I$  which remained suppressed for an additional hour before recovery began. However,  $\Sigma Tr_I / \Sigma Tr_D$  was 68% from 1030 to 1600 h (Table 1) and was 78% from 0800 to 2000 h (data not shown), which was 20% higher than the daily total predicted by Thompson et al. (1993). Similar  $ET_I$ ,  $Tr_I$ , and  $T_{c(I)}$  responses to microclimatic changes occurred on DOY 240 (Figs. 4 and 5, Table 2), DOY 193 (07/12/90), and DOY 212 (07/31/90) (data not shown).

Visual inspection following impact sprinkler irrigation found that the canopy dried typically within 0.5 h after the irrigation application ceased. Due to the rapid dry-off of the plant canopy, most  $I_{gross}$  losses were confined to the period of irrigation application. Gross interception losses for DOY 236 and DOY 240 are summarized in Tables 1–2. Estimated  $I_{gross}$  losses of the total net irrigation application were 15% (2.31 mm) on DOY 236 and 10.3% (2.2 mm) on DOY 240. Immediately after the irrigation ceased (1245 h) on DOY 236, measured  $ET_I$  was 0.08 mm/h higher than  $ET_D$  for 0.25 h, but then declined 0.24 mm/h lower than  $ET_D$  (Fig. 6). At 1245 h, measured evaporative loss associated with stored canopy water and soil water ( $ET_I - Tr_I$ ) was 0.68 mm/h, or 0.17 mm over a 0.25 h period. For 0.5 h (1400 h) immediately after the DOY 240 irrigation,  $ET_I$  was 1.5 times that of  $ET_L$  (Fig. 4), but then declined 0.16 mm/h lower than  $ET_L$  at 1430 h. The measured evaporation ( $ET_I - Tr_I$ ) during that period was 0.76 mm/h, or 0.38 mm (Table 2). This suggests an initially high  $ET$  rate associated with drying of canopy-intercepted water, followed by suppression of  $ET_{Tr}$ , probably due to microclimatic modification.

Measured transpiration suppression during the irrigation reduced  $I_{gross}$  losses to  $I_{net(E)}$  losses of 7.8% on DOY 236 and 6.9% on DOY 240. Continued transpiration suppression following the irrigation resulted in final  $I_{net(E)}$  losses of 4.7% on DOY 236 and 5.5% on DOY 240. Transpiration suppression during and after a 25.6 mm irrigation application on DOY 193 reduced  $I_{gross}$  losses from 10% to 6.7% (data not shown). Due to variable solar radiation, reductions of  $I_{gross}$  losses on DOY 212 were limited to the time of irrigation, with  $I_{net(E)}$  losses of 5% for a 20.7 mm application (data not shown). Gross interception losses



**Fig. 6** Measured evapotranspiration ( $ET$ ) and transpiration ( $Tr$ ) for impact sprinkler and LEPA irrigation events, and associated solar radiation. Vertical lines represent the beginning and end of the irrigations



**Fig. 7** Changes in within-canopy vapor pressure deficit ( $VPD$ ) during and after impact sprinkler and LEPA irrigation events. Vertical lines represent the beginning and end of the irrigation

modeled by Thompson et al. (1993) were 7.4% of the 38.7 mm water application, but reduced soil water evaporation and transpiration resulted in an effective loss of applied irrigation water of 3.1%.

Predicted  $I_{net(P)}$  losses calculated the magnitude of evaporation suppression from aerodynamic and canopy

**Table 1** Impact sprinkler (I) irrigation application rate ( $A_p$ ), estimated gross interception loss ( $I_{gross}$ ), net interception loss ( $I_{net}$ ) either predicted (P) or estimated (E), their percent of sprinkler irrigation application ( $A_p$ ), evapotranspiration (ET), transpiration (Tr) for both impact sprinkler irrigation and no irrigation (D), and canopy temperature ( $T_c$ ). Time of irrigation was 1045–1210 h CST DOY 236 (08/24/90)

Time	ET <sub>I</sub>	Tr <sub>D</sub>	Tr <sub>I</sub>	A <sub>pI</sub>	I <sub>gross</sub>	I <sub>net(E)</sub>	A <sub>pI(E)</sub>	I <sub>net(P)</sub>	A <sub>pI(P)</sub>	T <sub>c(I)</sub>
h	mm/h						%	mm/h	%	°C
1030	0.50	0.70	0.64							29.1
1100		0.76	0.58	2.52	0.88	0.70	27.8	0.49	19.4	27.7
1130		0.84	0.28	13.68	1.14	0.58	4.2	0.57	4.1	23.6
1200		0.88	0.18	10.94	1.24	0.54	4.9	0.57	5.2	23.8
1230		1.02	0.22	3.42	1.36	0.56	16.4	0.55	16.1	24.6
1245	1.12	1.04	0.44							26.1
1300	0.88	1.06	0.66							27.6
1400	0.84	0.80	0.68							26.7
1500	0.82	0.84	0.74							27.4
1600	0.74	0.72	0.70							27.1
Σ (mm)		4.99	3.40	15.28	2.31	1.19		1.08		

**Table 2** Impact sprinkler (I) irrigation application rate ( $A_p$ ), estimated gross interception loss ( $I_{gross}$ ), net interception loss ( $I_{net}$ ) either predicted (P) or estimated (E), their percent of sprinkler irrigation application ( $A_p$ ), evapotranspiration (ET), transpiration (Tr) for both impact sprinkler irrigation and LEPA irrigation (L), and canopy temperature ( $T_c$ ). Time of irrigation was 1145–1330 CST DOY 240

Time	ET <sub>I</sub>	Tr <sub>L</sub>	Tr <sub>I</sub>	A <sub>pI</sub>	I <sub>gross</sub>	I <sub>net(E)</sub>	A <sub>pI(E)</sub>	I <sub>net(P)</sub>	A <sub>pI(P)</sub>	T <sub>c(I)</sub>
h	mm/h						%	mm/h	%	°C
1130	0.76	0.58	0.70							29.6
1200		0.60	0.48	6.02	1.08	0.96	15.9	0.33	5.5	26.1
1230		0.58	0.22	11.30	1.04	0.68	6.0	0.35	3.1	23.9
1300		0.56	0.16	15.66	1.16	0.76	4.9	0.35	2.2	24.1
1330		0.70	0.14	9.82	1.12	0.56	5.7	0.35	3.6	23.9
1400	1.12	0.74	0.36							28.0
1415	0.76	0.74	0.46							28.5
1430	0.64	0.74	0.56							29.1
1500	0.70	0.74	0.64							29.0
1530	0.76	0.70	0.66							28.8
1600	0.78	0.64	0.62							
Σ (mm)		3.29	2.27	21.40	2.20	1.48		0.69		

surface resistances to vapor transport and changes in canopy temperature. On DOY 236,  $I_{net(P)}$  loss was within 10% of  $I_{net(E)}$  losses, but were 47% lower on DOY 240. On both days, the canopy temperatures (Tables 1 and 2) and the  $r_c$  values (81.9 s/m on DOY 236 and 75.3 s/m on DOY 240) used in the calculations were very similar, but the friction velocity (which approximates aerodynamic resistance) on DOY 240 was 0.48 m/s while on DOY 236 it was 0.22 m/s. Estimated losses were also 2.3 times greater than predicted losses on DOY 193, when the crop had low canopy resistance (36.7 s/m) but high friction velocity (0.35 m/s). While the total predicted  $I_{net(E)}$  and  $I_{net(P)}$  losses were less than 8% of the total impact sprinkler irrigation application for all days, low application rates at the beginning and end of the irrigation resulted in higher percentages of losses ( $A_{pI(E)}$  and  $A_{pI(P)}$ ), with 16–28% of the applied water being evaporated. The predicted loss rates during these periods, however, were not substantially larger than those at higher irrigation application rates.

cant offsets in these losses through transpiration reduction require that a substantial portion of evaporative demand be met through transpiration, which occurs only during mid-day. Overall, total interception losses were limited to less than 8% of the total day time impact sprinkler irrigation application ranging between 15 and 25 mm. Transpiration suppression due to evaporation of canopy-intercepted water and microclimatic modification resulted in net crop canopy interception losses between 5.1 and 7.1% of the applied irrigation water. Transpiration recovery to near pre-irrigation levels was rapid, with additional transpiration suppression of 1–3% occurring only on days with high solar radiation.

Typically, evaporation of surface water deposited by LEPA had little effect on ET or transpiration, except on days with high vapor pressure deficit; this limited any increases in LEPA irrigation application efficiency. The wetting of only alternate furrows which occurred in this study most likely minimized the impact of soil water evaporation on the microclimate.

## Conclusions

The magnitude of canopy-intercepted irrigation losses is limited by the storage capacity of the canopy, and the amount of available energy used for evaporation. Signifi-

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